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Solid Waste :
A New Natural Resource

Prepared by the Staff of the Fluidized Bed Gasification Project

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An experimental program for converting municipal refuse into fuel gas of high thermal efficiency using the fluidized bed pyrolysis process. The fluidized bed is a cylinder containing a bed of high silica sand resting on a gas distribution plate and when compressed gas passes through the distribution plate any solid will attain the temperature of the sand. Factors affecting the pyrolysis will have to be considered in developing a municipal refuse gasification process.

Eight figures are presented in the report.

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SOLID WASTE

A NEW NATURAL RESOURCE

A brochure presenting the advantages of converting municipal waste into a high energy fuel gas using the fluidized bed pyrolysis process.

Prepared by the Staff of the Fluidized Bed Gasification Project

"Solid waste material represents a national resource and will in time be a major one. Return of fractions of solid wastes to economical reuse must in the long run become common practice and must be a national objective" . . . National Academies Committee

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May 1971

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A NEW NATURAL RESOURCE

"4 . . 3 . . 2 . . 1 . . lift off. We have lift off." And so begins another moon flight. Soon two more Americans will stand on the surface of the moon. We are a nation who has sent men to the moon, and yet more than two-thirds of our population is served by inadequate refuse treatment facilities. The problem of solid waste disposal has plagued man since antiquity as is evidenced by an old Roman signpost that read, "Take your refuse farther or you will be fined." It is even reported that the crooked streets of ancient Athens were "heaped with refuse." Even the Bible gives reference to being "cast into the fires of Gehenna" which literally meant to be cast into the obnoxious burning refuse dump. A solution to our ever increasing national solid waste pollution problem is being investigated by the Chemical Engineering Department of West Virginia University. The West Virginia University Process takes the solid waste and uniquely converts it into a high energy gas which can help supplement our diminishing natural gas resources.

The solid waste pollution problem has reached extremely alarming proportions. At present, the United States produces 7 pounds of solid waste per capita per day. Annually, this amounts to 268 million tons of solid waste production, or over 1 ton of waste discarded by every man, woman, and child. By 1980, some 235 million people are expected to be generating 8 pounds per person per day of solid wastes or more than 340 million tons per year. The current annual cost of refuse collection and disposal is well above $4.5 billion, or more than for any other public service except schools, roads, and national defense.

The present methods for disposing of municipal waste are alarmingly inadequate, and their inadequacy can only increase in the future. Unlike air and water pollution which we attempt to hide by dilution, we have tried concentration as the solution to the solid waste pollution problem. Over 90 per cent of the collected municipal solid waste is disposed of in land fill projects, but what of the highly populated metropolitan areas? These cities dispose of their wastes in lakes, rivers, oceans, or pay large transportation costs to move their solid waste to land fill areas. Another popular solution to solid waste pollution is municipal incineration which disposes of 6 per cent of the collected solid waste. But municipal incineration has a high air and water pollution potential, large capital costs, and high operating costs. Air pollution is in the form of smoke, soot, SO_2, HCl, and NO_x emissions. Also, there is a residue left that must be disposed of after incineration. The United States is on the verge of a solid waste disposal crisis that threatens our environment by potentially increasing air and water pollution. To quote a Pogo observation: "We have met the enemy and he is us."

It is only too clear that we must find an alternative solution to the solid waste problem. The President's Council on Environmental Quality told Congress in August, "Solid waste etches a trail of visible blight that leaves few corners of the country unspotted." It was at this time that Congress passed the Resource Recovery Act of 1970 that outlines the path we are to take in solving our solid waste problem. It suggests we are to reduce the cost of solid waste disposal by recovering useful resources for recycle back to our economic system with less pollution of our environment. The National Academies Committee said, ". . . . .Solid waste material represents a national resource and will in time be a major one. Return of fractions of solid wastes to economical reuse must in the long run become common practice and must be a national objective." In light of this, it would appear that the 7 to 8 pounds per day per person of the refuse we are generating is not solid waste but wasted solids—a new natural resource.

THE NEED IS CLEAR

The United States has been fortunate to have had during its technological revolution ample supplies of low-cost, high-energy fuel. Without these resources, the United States would not have achieved its present position of technological leadership. It will be impossible to continue or maintain the nation's technological level without a continuing source of low-cost plentiful energy.

The energy consumed by the nation results in utilizing fossil fuel resources, and the consumption of these fossil fuels is much faster than they are being generated. Future estimates indicate that the supplies of natural gas will last only 11 more years while oil reserves will last 25-30 years, and present coal supplies will last 500 years. The fossil fuel resources are continuing to be depleted without replacement, and it is becoming more difficult, if not dangerous, to borrow from the future. The need is clear. We must begin to use more wisely our fossil fuel resources.

A typical analysis in Table 1 shows municipal waste to be over 80 per cent carbonaceous matter and over 60 per cent cellulosic material. Through the process of pyrolysis (chemical decomposition by heat in the absence of

TABLE 1. Municipal Refuse Components

COMPONENT	AS RECEIVED (Wt. per cent)	PICKED–DRIED (Wt. per cent)
Paper	48.0	48.7
Plastic; Leather; Rubber	2.0	2.8
Garbage (Food Wastes)	16.0	11.1
Grass; Tree Leaves	9.0	6.9
Wood	2.0	2.1
Textiles	1.0	0.7
Glass, Ceramics, Stones	14.0	16.6
Metals	8.0	11.1
	100	100

oxygen) the carbonaceous material can be converted into a readily available fuel gas that can be used as a substitute for natural gas. This would help to conserve our depleting natural gas reserves. Another factor to consider is that municipal waste is not depleting with time, as are the fossil fuels, but is actually being generated in larger amounts each year. This approach to the solid waste pollution problem is being investigated under a grant from the Solid Waste Office of Research and Monitoring of the Environmental Protection Agency by the Chemical Engineering Department of West Virginia University.

FLUIDIZED BED PYROLYSIS

The actual process being investigated at West Virginia University is pyrolysis of municipal waste using a fluidized bed gasifier. The fluidized bed is simply a cylinder containing a bed of high silica sand resting on a gas distribution plate. Compressed gas passes through the distribution plate and into the bed suspending each solid sand particle. This bed is fluid in the sense that a rock placed in the bed will sink while a piece of wood will float. If an opening is made in the cylinder wall, the fluidized sand will pour out while the unfluidized sand will not. These phenomena are illustrated in Figure 1.

The fluidized bed was first used as a unit operation to gasify solid fuels (brown-coal) by Fritz Winkler in Germany in 1926, and near the end of WWII carbonaceous waste materials were gasified by the Winkler process. Since solid waste is highly carbonaceous, an investigation of a fluidized bed process to gasify solid waste appeared attractive and unique.

Initial investigations were performed using the fluidized bed as a solid waste incinerator. The fluidized bed operates at practically isothermal conditions and any solids introduced into the bed will immediately attain the temperature of the sand. This characteristic allows for rapid and complete combustion of the solid waste particles. The heat of combustion is immediately carried away by the fluidized sand to be used elsewhere in the bed. The fluidized sand thus acts as a thermal flywheel in that it supplies the heat of reaction to allow the solid waste to burn and then removes the heat of combustion to another area of the bed. It was primarily for this reason that investigations were conducted to study pyrolysis of municipal refuse in fluidized beds.

The process of pyrolyzing the municipal refuse is conducted in a 1500^0F fluidized sand bed in an oxygen free atmosphere. The cellulose molecule is introduced into the bed as municipal refuse and the thermal flywheel effect immediately brings the refuse to 1500^0F where the cellulose molecule will burn. Due to the absence of oxygen in the bed atmosphere, the molecule instead of burning actually explodes. In this explosion, as in any explosion, the molecule is randomly blown apart. The fragments of the exploded cellulose molecule form methane, carbon dioxide, hydrogen, carbon monoxide, and water molecules. A simple representation of this process is shown in Figure 2. Each cellulose molecule introduced into the fluid bed gasifier undergoes this same chemical decomposition. A by-product of the chemical decomposition is solid activated carbon char which is carried out of the fluidized bed with the pyrolysis gas. The gas and char formed from the chemical decomposition of municipal refuse are of prime interest as sources of energy recycle to our economic system.

If cellulose is burned in an oxygen rich atmosphere, as is the case in incineration, carbon dioxide gas is produced. This is the lowest or most regressive ecological energy level. In other words, this gas can make no positive

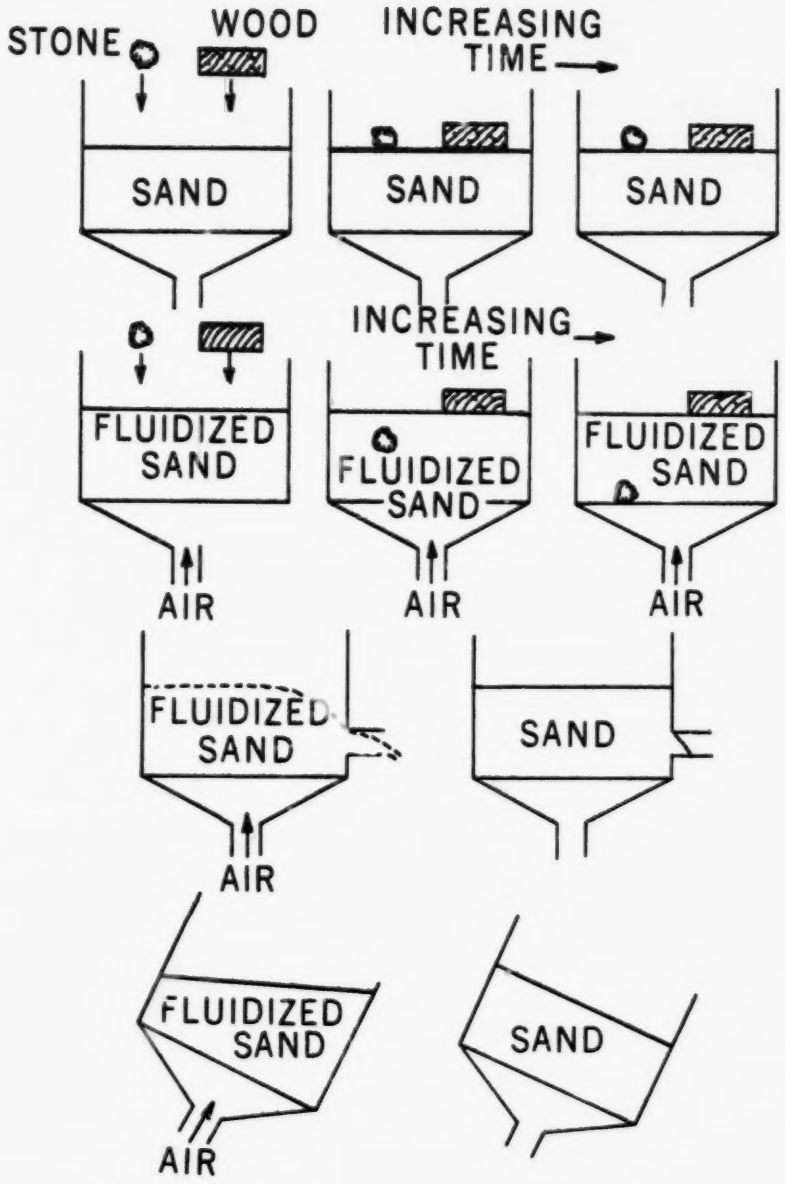

Figure 1-A Simple Illustration of the Similarities Between Fluidized Sand and a Liquid

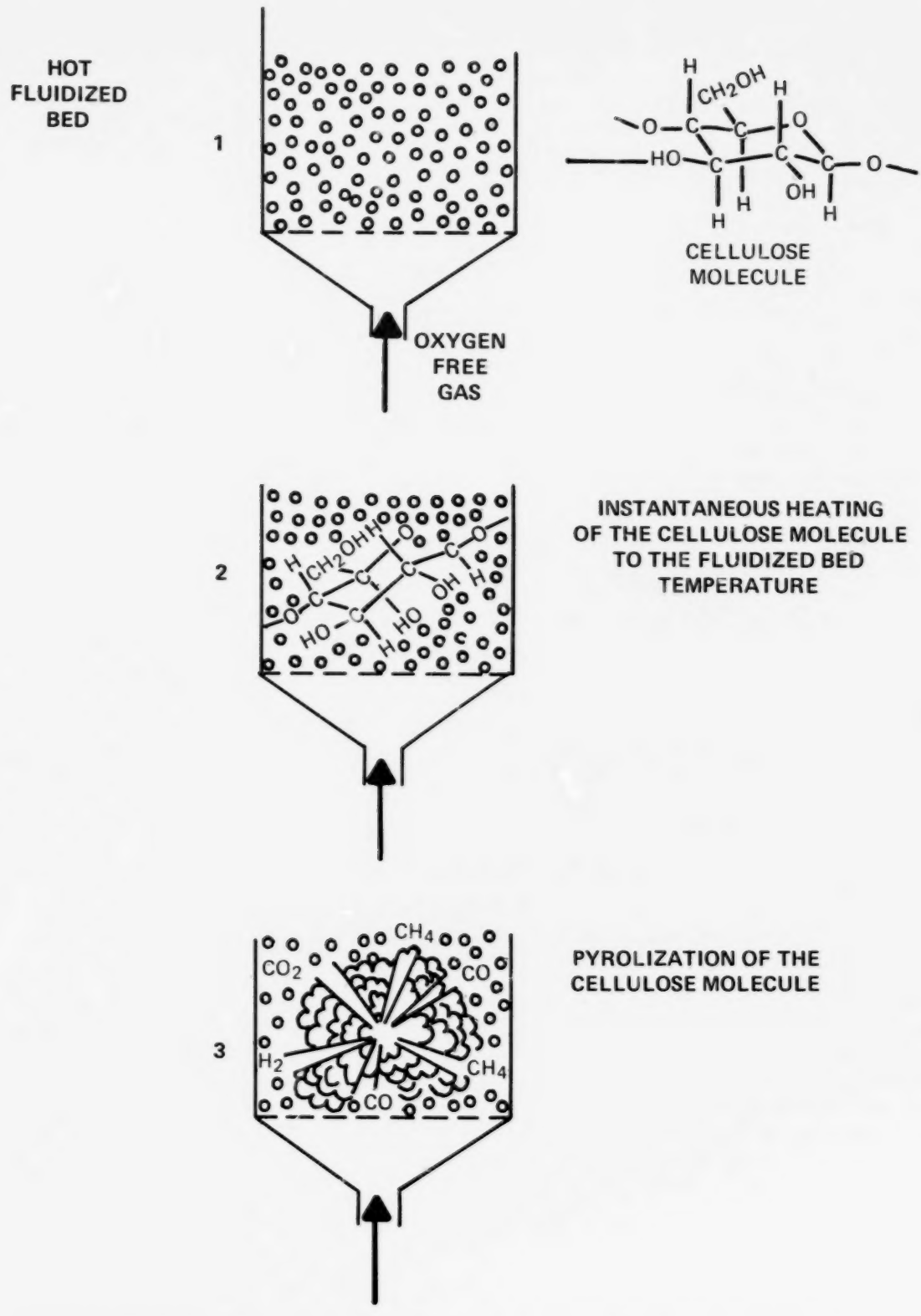

Figure 2-Chemical Reduction of The Cellulose Molecule. (1) and (2) Show The Cellulose Molecule Being Introduced Into the Hot Fluidized Bed. (3) Shows the Cellulose Molecule Literally Being Rearranged by Exploding into Its Pyrolysis Gas Products.

contribution to our energy resources, and can only be regenerated by the carbon cycle of plant growth and fossilization. The carbon cycle is shown in Figure 3. However, when the cellulose molecule is "burned" in an oxygen-free atmosphere the produced pyrolysis gas is, in reference to ultimate resources conservation, ecologically less regressive than the combustion products from incineration. Pyrolysis converts municipal waste to products with a potentially positive energy contribution rather than to carbon dioxide. The pyrolysis gas can be thought of as water near the top of a waterfall—energy can be produced in turning a paddle wheel. The products of combustion are represented by the water at the bottom of the falls—no possible energy production value. The only possible way to derive energy from the water at the bottom of the falls is to pump it (the carbon cycle) back to the top of the falls. Pyrolysis of municipal refuse efficiently in the fluidized bed gasifier allows recycle of a potentially important source of energy and raw materials to our environment as well as reducing overall pollution of land, air, and water.

PROCESS DEVELOPMENT

The conversion of fossil fuels into fuel gas or pipeline gas is presently accomplished by complex processes. These processes operate at high temperatures and pressures, require large numbers of skilled personnel, and demand large capital investments. Two such processes which are considered economical to operate in Europe and Asia are the Lurgi process and the Koppers Totzek process. The Lurgi process requires high pressure, pure oxygen, and steam to gasify coal. The Koppers Totzek process operates at 900°C with moderate pressure, and requires steam and 98.5 per cent pure oxygen to gasify lignite. Both of these processes require a steam generation plant, as well as an oxygen producing facility. It is easy to see why the capital and operating costs are high, yet it is economical for these plants to produce fuel gas. The gas produced from these processes is not equivalent to natural gas, but it is compressed and pumped as far as 200 miles in pipelines for industrial and domestic use. The fuel gas produced has a heating value of less than half that of natural gas. The economical success of these processes lies chiefly in the fact that Europe and Asia do not possess large supplies of natural gas. This is not the case in this country, but as mentioned earlier, our resources of natural gas will only last an estimated 11 years.

It is clear that the types of processes employed in fossil fuel gasification are too complex for the pyrolysis of municipal refuse. A new attitude must be adopted; process complexity and capital costs must be minimized and additional supporting systems must be avoided.

The factors affecting pyrolysis must also be considered in developing the municipal refuse gasification process. Literature concerning pyrolysis of solid waste is limited, but cellulose pyrolysis has been studied. Since cellulose is the major component of solid waste, an understanding of its thermal decomposition would aid in understanding and predicting what to expect from the pyrolysis of municipal refuse.

Some of the major points to consider in the pyrolysis of cellulose and solid waste are summarized below.

- Thermal degradation of cellulose is a complicated phenomena and several theories have been presented to explain the observed reactions. Figure 4 represents the general reactions that are considered to be involved in the pyrolysis and the combustion of cellulose. The data and results from various experiments are scattered and any inferences drawn from these are considered possibilities rather than established facts. The relative proportion of flammable gases produced varies according to the temperature, time, sample geometry, and the environment of the pyrolyzing cellulose. However, certain general observations can be made.
- In slow heating, decomposition proceeds according to an orderly arrangement forming increasingly more stable molecules, richer in carbon, and converging toward graphite carbon. In very rapid heating, the molecules are literally torn apart into volatile fractions with almost no possibility of orderly arrangement. Slow pyrolysis at low temperatures yields char and oxygenated gases, and fast pyrolysis yields flammable gases.
- In pyrolysis of solid waste, it was found that the rate of heating was an important consideration, that the yield of fuel gas increased with the heating rate, and that flash pyrolysis would result in a significantly higher yield of energy in the gas phase. This is in agreement with the results discussed above for the pyrolysis of cellulose. The experimental technique used did not allow for really rapid pyrolysis, and it would be assumed that by proper choice of the process, higher yields would be attainable. The temperature used was 1500°F, and it was also noted that the char produced could be further gasified to increase the gas yield.

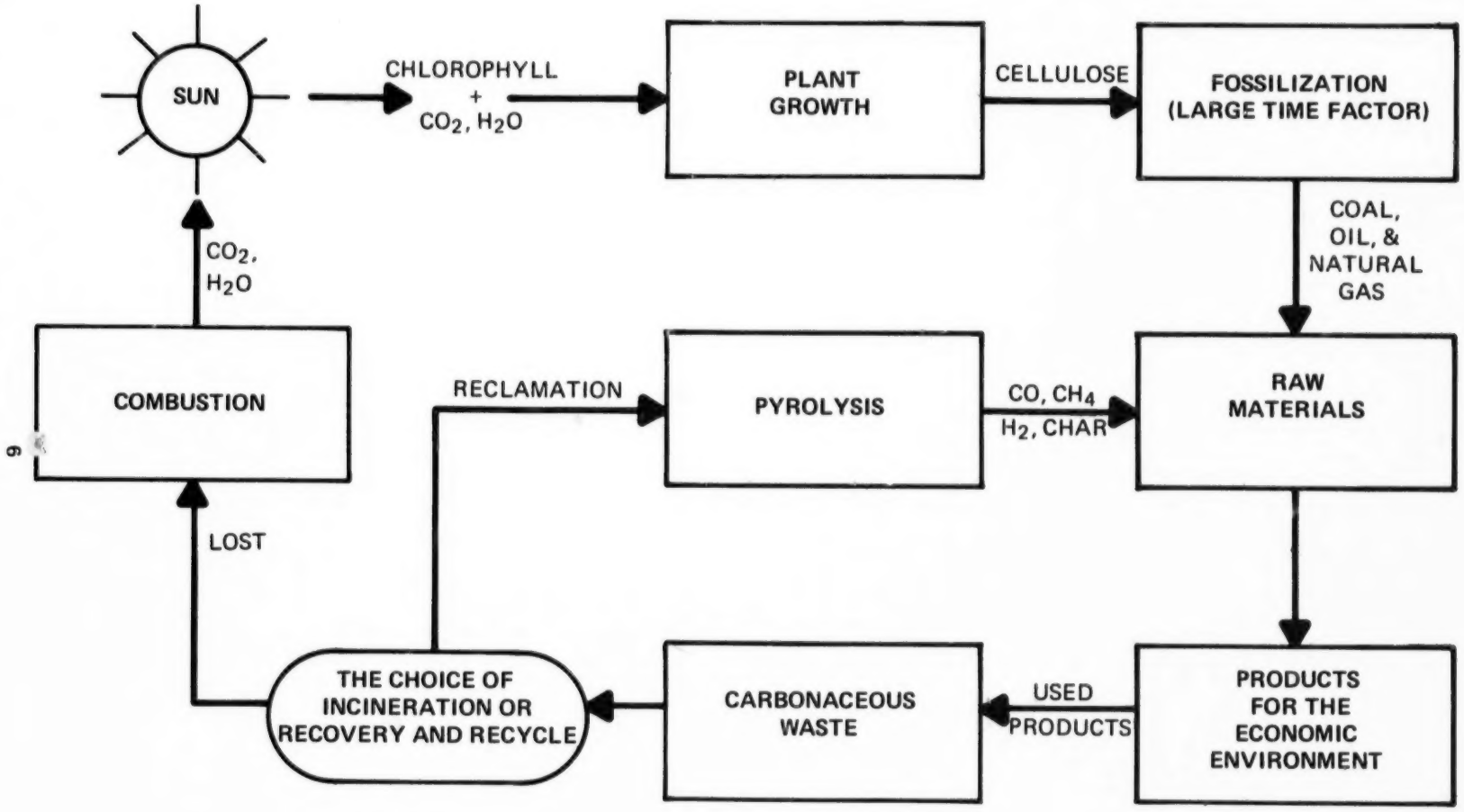

Figure 3-Pyrolysis Provides a Means for Reintroducing into The Energy Cycle What Is Now Lost to Waste.

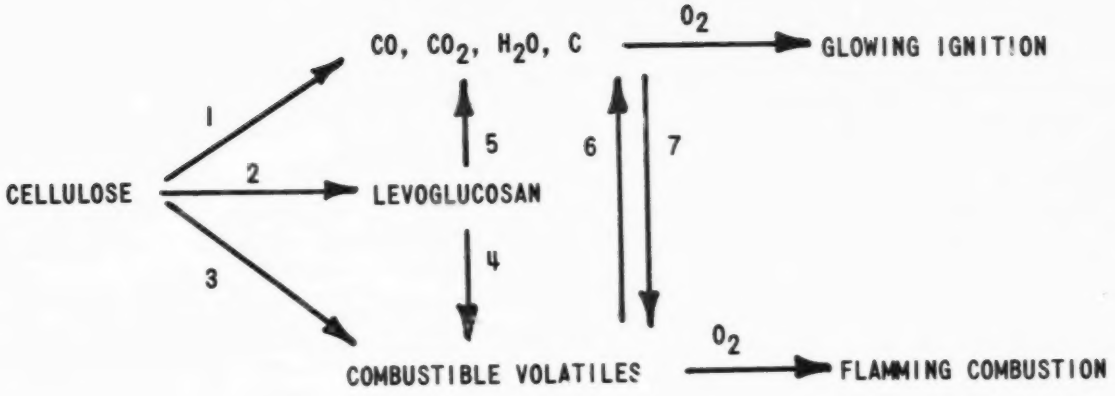

Figure 4-The General Reactions Involved in Pryolysis and Combustion of Cellulose

In developing our process for conversion of municipal refuse to a usable energy source for recycle to our economic system, the following items were considered:

1. Capital costs and operating expenses are to be minimized.
2. High pressure systems are to be avoided (atmospheric is desirable).
3. The use of pure oxygen and steam as raw materials is not to be considered.
4. The number of skilled operating laborers is to be minimal.
5. The process is to be flexible in size so as to accommodate the municipal refuse output of the particular area that the facility serves.
6. The process need not generate the equivalent of natural gas to be considered successful. The gas generated must be of sufficiently high value to be compressed and transported a limited distance economically.
7. Very rapid heat transfer to each solid waste particle to be pyrolyzed with isothermal operation is desirable.
8. High temperature heating capabilities should exist.

PROCESS DESCRIPTION

Pyrolysis of municipal refuse is an endothermic process. It becomes necessary to rapidly heat the refuse to a high temperature and then add enough extra energy to allow chemical decomposition to occur. This process must be accomplished in the absence of oxygen. The process of combustion requires the same treatment in the presence of oxygen. The main difference is due to the fact that the combustion reactor is exothermic and the ensuing heat must be effectively removed. It would appear that an efficient fluidized bed pyrolysis process could derive the heat required for chemical decomposition from a fluidized bed combustion unit.

The fluidized bed system being developed by the Chemical Engineering Department at West Virginia University for the Solid Waste Office of Research and Monitoring of the Environmental Protection Agency uses the heat given off by the combustion of pyrolysis char to supply the energy needed in the municipal refuse pyrolysis reaction. The oxygen required for combustion is supplied by compressed air, and in order to prevent the nitrogen in the air from diluting the pyrolysis gas, the two reactions are carried out in separate reaction vessels. The transfer of energy between the two reactors is accomplished in a manner similar to that developed by the petroleum industry in manufacturing high octane gasoline. Each vessel contains equal depths of fluidized sand particles, and the sand can be induced to flow from one vessel to another. The sand flow from the combustion reactor at 1750°F to the pyrolysis reactor at 1500°F supplies the heat necessary for the chemical decomposition of municipal refuse to occur. The solid feed to the pyrolysis unit is municipal refuse, while that to the combustion unit is the solid char formed from the municipal refuse pyrolysis reaction. The high heat transfer rate and isothermal conditions of the fluidized bed are very desirable for fuel gas production. A simple schematic of this process is shown in Figure 5.

EXPERIMENTAL GAS PRODUCTION RESULTS

The following is a short description of the experimental results obtained from the fluidized bed pyrolysis of municipal refuse. The tests were conducted using the atmospheric pilot plant fluidized bed gasifier equipment (Figure 6) developed at the Chemical Engineering Department at West Virginia University with the cooperation of the Solid Waste Office of Research and Monitoring. The results are presented in Table 2.

The pyrolysis gas could conceivably be treated through a methanation process to raise the heating value to that of natural gas (see Table 4).

Table 3 presents the characteristics of the fuel gas produced by the Koppers Totzek process, the Lurgi process, and solid waste fluidized bed pyrolysis system. Also, the energy recovery from the solid waste fluidized bed pyrolysis process is about 70 per cent while that for the Koppers Totzek and Lurgi processes is between 60 and 65 per cent.

Examining Table 3 clearly shows that the gas produced by the fluidized bed pyrolysis process is superior to that produced by either of the other processes. The heating value of the gas produced by the fluidization method is considerably higher than either of the other processes. The Koppers Totzek and Lurgi processes require high pressure, coal or lignite, steam, and pure oxygen. The fluidized bed process uses atmospheric pressure, air, and municipal refuse. Refuse pyrolysis produces better gas, conserves the fossil fuel and natural gas resources, and helps solve the solid waste pollution problem.

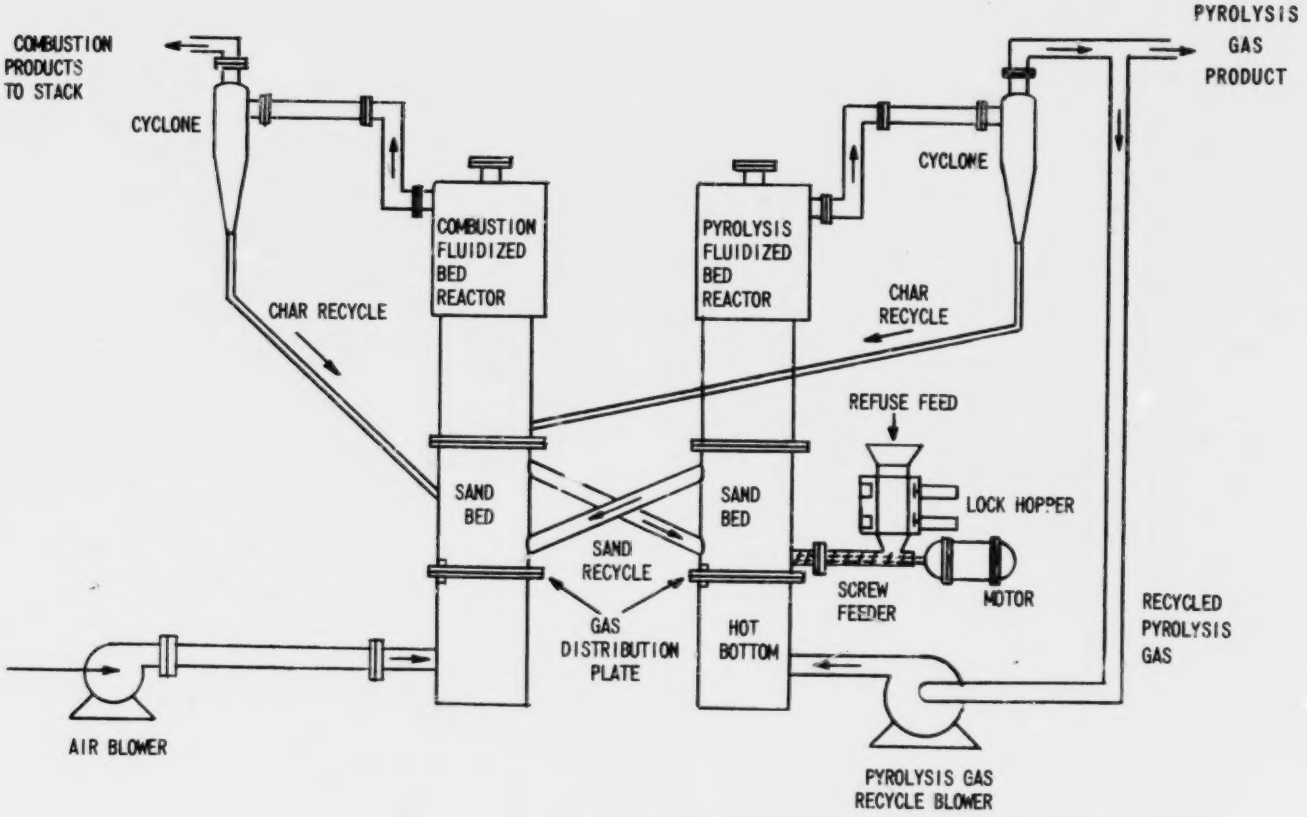

Figure 5-A Simple Schematic of the Municipal Refuse Pyrolysis Process Using Fluidized Sand Recycle and Char Recycle.

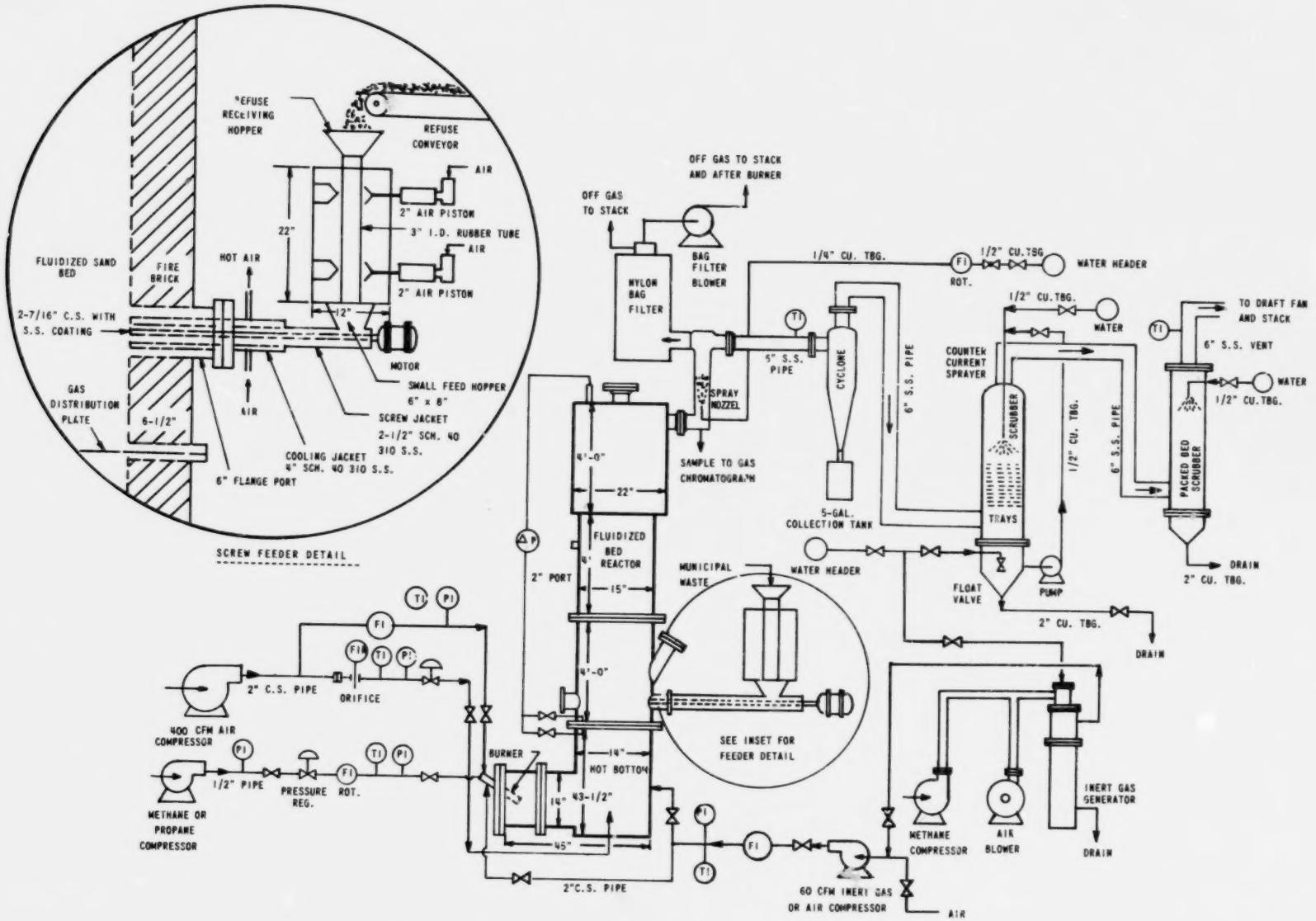

Figure 6-Flowsheet for Fluidized Bed Pyrolysis Reactor

TABLE 2. Pyrolysis of Municipal Refuse Tests Results

Component	Proximate Municipal Refuse Analysis	Proximate Activated Char Analysis	Gas Production SCF/LB Solid Fed (Dry Basis)	Dry Gas Composition (Vol. %)	Dry Gas Composition (CO_2 Free)
CO_2			1.40	16.3	0.0
CO			3.04	35.5	42.4
CH_4			0.95	11.1	13.3
H_2	3.56	2.95	3.18	37.1	44.3
Carbon	25.15	60.82			
Ash	36.54	11.12			
Heating Value BTU/SCF Dry				366	437

TABLE 3. Comparison of the Koppers Totzek and Lurgi Processes to the Fluidized Bed Pyrolysis of Solid Waste

	Koppers Totzek Process	Lurgi Process	Fluidized Bed Process
SOLID FED	LIGNITE	COAL	SOLID WASTE
CO_2 (Vol. %)	14.8	25.6	16.3
O_2	0.4	0.0	0.0
CO	46.2	24.4	35.50
H_2	31.9	37.3	37.10
CH_4	2.5	10.3	11.10
N_2	4.2	1.8	0.0
Unsaturated Hydrocarbons	0.0	0.6	–
Heating Value, BTU/SCF Dry	210	312	366

400 TON PER DAY FACILITY

The following is a short description of the equipment used to process 400 tons per day of municipal refuse which has an average moisture content of 30 per cent. This description is not meant to be a detailed design layout but merely gives an estimate of the major equipment sizes along with the expected pyrolysis gas production.

The schematic of the entire municipal refuse fluidized bed pyrolysis system is shown in Figure 7.

The combustion unit is a fluidized bed 3.5 feet in diameter and 20 feet high. The sand bed height is 4 feet with a harmonic mean particle diameter of 0.025 inches. The combustor will be fed the recycled char produced in the gasifier unit at a rate of 31,500 #/hr. and will operate at 1750°F. This bed will operate at three times the minimum fluidization velocity using 2.1 MMSCF/DAY of air. The off gas from the combustor will pass through two cyclones to effect gas clean up. The first cyclone will remove large solid particles while the second will remove the smaller particles. The char removed from the cyclones will be returned to the combustor for fuel. The combustion products will then be passed through a heat exchanger to preheat the air entering the combustor for heat conservation.

The fluidized pyrolysis unit will be 7.5 feet in diameter with an overall height of 20 feet. The bed height and sand harmonic mean diameter are the same as for the combustor. The pyrolysis unit will operate at 1500°F and will gasify 400 tons per day of municipal refuse. The gas to fluidize the pyrolysis unit will be supplied by recycling the

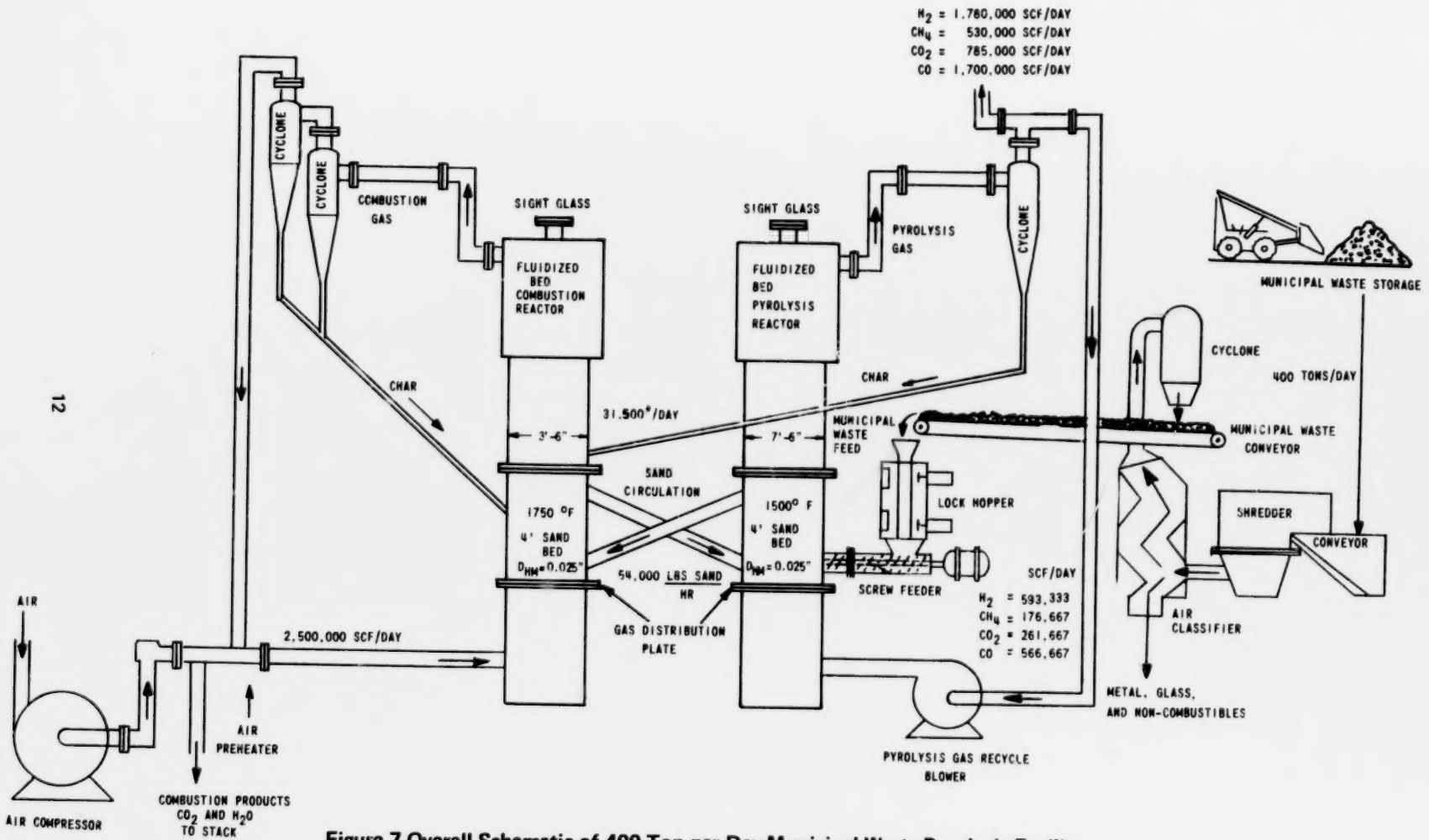

Figure 7-Overall Schematic of 400 Ton per Day Municipal Waste Pyrolysis Facility.

pyrolysis gas. One-third of the gas produced will be recycled, and the bed will operate at three times the minimum fluidization velocity. The pyrolysis gas stream will pass into a cyclone to remove the product of activated carbon char produced in the pyrolysis reaction. This char is fed to the combustion unit to supply the heat necessary to keep the fluidized sand temperature at 1750°F. The off gas may be passed through an optional processing system. The gas could go through a water gas shift reactor, a carbon dioxide scrubber, a clean up washer, and finally, a methanator to convert all the pyrolysis gas to methane. This system is purely optional as the gas coming directly from the pyrolysis unit is an immediately usable energy source. The energy required to maintain the pyrolysis unit at 1500°F is obtained from the sand circulating from the combustion unit at 1750°F. The sand circulation rate is approximately 54,000 pounds of sand per hour.

The refuse feed system bears some mention. Most of the system has already been developed for Combustion Power Company's CPU-400 system. The system consists of a refuse storage pit from which the refuse is removed as needed and fed to the conveyor belt by a mechanical lift. The refuse is passed to a sophisticated refuse shredder where the municipal refuse is reduced in size. The refuse is passed through an air classifier where 90 per cent of the metal, glass, and heavy objects are removed. The classified refuse is then fed by conveyor to a lock hopper-screw feeder apparatus where the refuse is fed directly into the fluidized bed.

The amounts of pyrolysis gas at different steps in the final gas processing are shown in Table 4 on a dry gas basis.

TABLE 4. Pyrolysis Gas Produced From 400 Tons Per Day of Municipal Refuse*

Component	Pyrolyzer Exit SCF/DAY (Dry Basis)	CO-Shift Exit SCF/DAY (Dry Basis)	CO_2 Scrubber Exit SCF/DAY (Dry Basis)	Methanator Exit SCF/DAY (Dry Basis)
CO_2	785,000	1,610,000	–	–
CO	1,700,000	870,000	870,000	–
CH_4	530,000	530,000	530,000	1,400,000
H_2	1,780,000	2,610,000	2,610,000	–
TOTAL	4,795,000	5,620,000	4,010,000	1,400,000

*Municipal refuse contains on the average 30 per cent moisture.

Four hundred tons per day of municipal refuse would be produced by a city of approximately 100,000 people. The average daily residential consumption of natural gas per capita is 150 SCF (dry). It can be seen from Table 2 that on a per capita basis per day 23 SCF of equivalent natural gas is produced from the pyrolysis unit. Thus, if all the municipal refuse produced per person per day were to be pyrolyzed by the fluidized bed method approximately 15 per cent of the daily natural gas requirement per person could be supplied. This amount of natural gas generation, while it does not flood the market with extra gas, does substantially subsidize the daily natural gas requirements of the United States. Thus, we are able to help solve the solid waste pollution problem, conserve our fossil fuel natural resources, and reduce potential air and water pollution!

UTILIZATION OF PYROLYSIS GAS

The actual pyrolysis gas from the fluidized bed has many direct applications including direct production of methane as described in the last section. This gas can be used in residential areas for heating and cooking, and for heating in steel mills. Other direct uses of this gas are for saline water conversion and steam production. Also, the gas could be burned in a jet engine type turbine for power generation. The pyrolysis gas could be used as a raw material in organic industries as well as in mineral and metallurgical industries.

The activated char produced by pyrolysis is also a valuable product. This char can be used directly as a solid fuel to perform some of the tasks of the pryolysis gas mentioned above. The char can be used for general purification and reclamation of liquid and gas streams. In particular, the char could be used to purify sewage sludge to obtain pure water and then the solids could be used as the energy source for the fluidized bed combustion unit. The activated char could be used to adsorb metallic ions. The char could also be used as the fuel for the fluidized bed combustion unit and could be circulated with the sand.

These processes are shown schematically in Figure 8.

PRESENT STATUS

The experimental program carried out at West Virginia University has established that municipal refuse can be converted into fuel gas with a relatively high heating value. It has been demonstrated that pyrolysis in a fluidized bed results in high gas yields with high thermal efficiency. The fluidized test facility used in the experimental program allowed for the feeding of crushed municipal refuse into a controlled atmosphere not unlike those anticipated for a full scale unit.

The work completed has established the viability of the process concept and allowed for evaluation of some of the environmental implications. Preliminary economic evaluations show the fluidized bed pyrolysis conversion process would not increase the cost of disposal but would actually allow for a significant return on the capital investment. It would be premature to give firm cost figures at this time. Before such values are presented a detailed engineering and economic evaluation of a full-scale facility, along with a detailed review of the effects on the total environment, must be completed. Further experimental effort is required before such a detailed evaluation can be completed.

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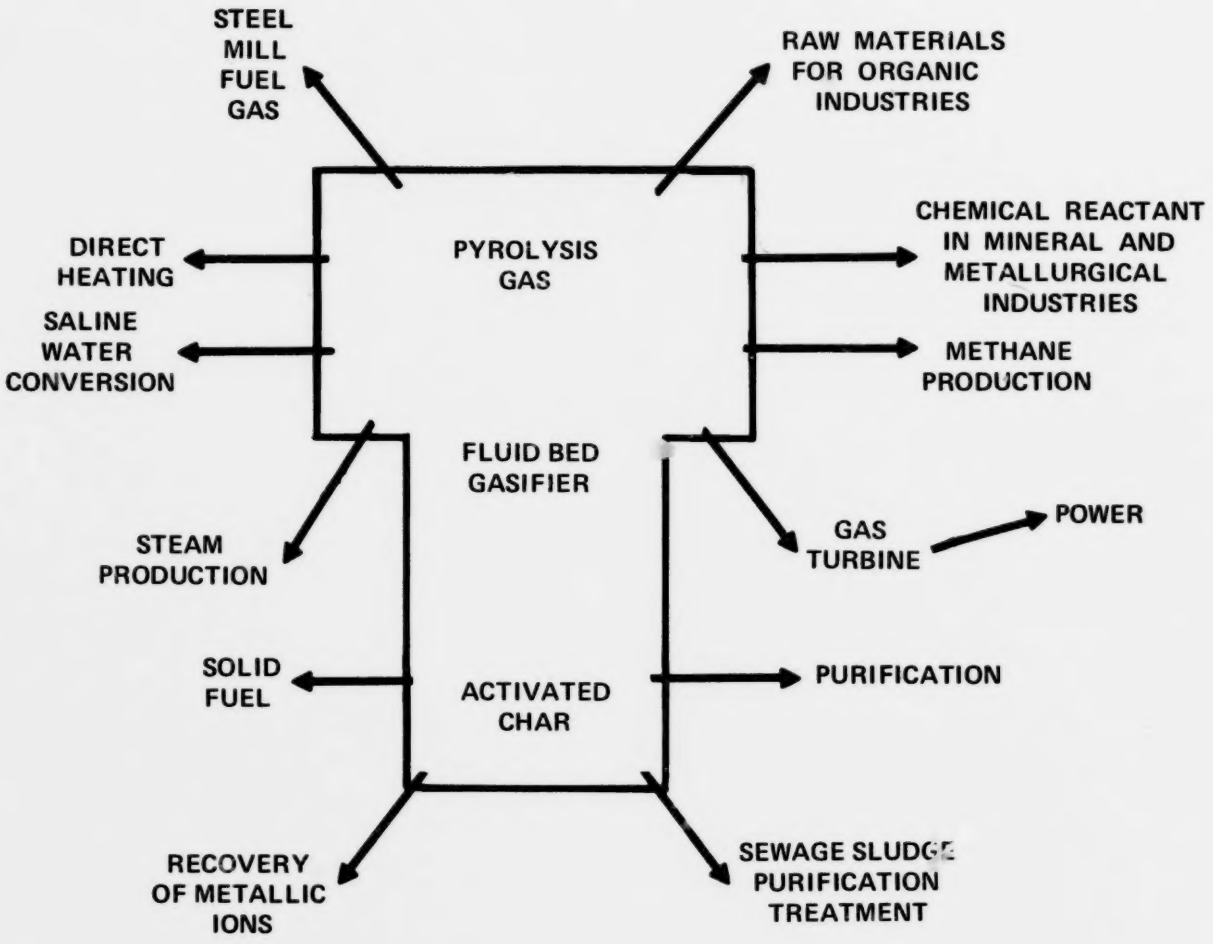

Figure 8-A Simplified Illustration of Possible Uses of the Gas and Char Products From the Pyrolysis of Municipal Refuse.

And Man created the plastic bag and the tin and aluminum can and the cellophane wrapper and the paper plate and the disposable bottle and this was good because Man could then take his automobile and buy his food all in one place and he could save that which was good to eat in the refrigerator, and throw away that which had no further use. And pretty soon the earth was covered with plastic bags and aluminum cans and paper plates and disposable bottles and there was nowhere left to sit down or to walk, and Man shook his head and cried, "Look at all this God-awful litter."

ART BUCHWALD, 1970